Cyber-Physical and Gentelligent Systems in Manufacturing and Life Cycle

Genetics and Intelligence – Keys to Industry 4.0

Edited by
Berend Denkena
Tobias Mörke
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In hot bulk metal forming processes, a regulated temperature control for dies permits an effective prevention of defects as well as a reduction in process interruptions by means of temperature stabilization. Furthermore, a reduction of thermally induced wear leads to a favorable decrease in tool costs. Such a die temperature control is of particular importance for processes like precision forging, in which geometrical integrity of the produced parts is the main concern (Chapter 3.2.6). See the following chapters for further information:

- 3.2.1 Feeling machine
- 3.2.2 Sensory workpieces
- 3.2.3 Feeling clamping system
- 3.2.4 Teachless process monitoring for single item production
- 3.2.5 Online monitoring and control of tool deflection in milling
- 3.2.6 Tempering control of forging processes by integration of cavities

## 3.2.1 Feeling machine

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### 3.2.1.1 Introduction

Nowadays, the trend in the production sector is edging toward more individual products. As a consequence, the producers have to adapt to a further increase in the variance of the product spectrum with decreasing its lot size. This development results in generally higher demands on intelligent systems for process monitoring and control that may help to reduce incurred additional costs in comparison to mostly cost-optimized series productions.
In order to enable systems for process monitoring and control, process signals are indispensable. The process force represents the most important physical size to describe a process during manufacturing. The first difficulty lies in the generation of signals, which correlate well with that force. To get such signals, sensors can be integrated in machine tool components. For instance, the incorporating of sensors in tool holders is achieved in [1], whereby the integration of the force sensor system led to a loss of stiffness and a sophisticated radio transmission of signals was needed. In the works [2,3], a sensing clamping system with piezo actuators was developed in order to reduce the vibration of workpieces during manufacturing. In the works [4,5], strain gauges and acceleration sensors were combined into a sensor network and integrated in a sensory clamping system. In a further step, this clamping system was combined with an adaptronic spindle and allows a robust force-related process monitoring with high sensibility [6].

Within the collaborative research center CRC 653 [7], “feeling” machine tools are being developed. This new kind of machines has the specific functionality to sense the vibrations and forces which occur during machining and to control the process in case of detected failures. The “feeling” machine tool is realized by the integration of sensory machine components, which are closely located to the process and directly guide the flux of force. In milling, the spindle slide, which carries the working spindle, or the clamping system, which holds the workpiece, are suitable for sensor application. The load detection is realized by strain measurements on the component structure. Such machine components are generally designed with respect to their stiffness in order to achieve the requirements for high machining accuracy and process stability. Therefore the strains in the structure are very low and thus can hardly be measured. A big challenge lies on achieving a component with a high sensitivity without lowering its stiffness.

### 3.2.1.2 Strain state in selected machine components

Finite element analyses were conducted in order to estimate the occurring strains in the spindle slide of a selected milling center. The resulting effective strains are illustrated in Fig. 3.2.1.1 for a force of 1 kN which is applied at the TCP in x- and y-directions. As the figure demonstrates, the achievable strain amplitudes in the structures are generally very low. Most of the structure shows strain values smaller than 10 μm/m. It can be concluded that an optimal placement for strain sensors is crucial to achieve reasonable sensor signal amplitudes.

### 3.2.1.3 Strain signal improvement in machine components

The strain in the structure of the machine component is measured by strain gauges. To raise the strain signal amplitudes, a concept to increase the measured strains is necessary. This can be achieved by locally adapting the force flux in the component
structure [8]. For the local force flux adaption, notches in the structure of the spindle slide [9,10] are investigated. The principle of the notching effect is depicted exemplarily in Fig. 3.2.1.2A. When a load is applied on a notched structure, local strain intensification occurs in the notch ground. By integrating strain gauges into the notch ground, higher signal amplitudes can be measured compared to a sensor application onto a nonnotched flat surface.

Fig. 3.2.1.1 Strain state in spindle slide structure.

Fig. 3.2.1.2 Signal amplification by notching effect.
The investigated notching approach suits very well with the extremely small sensors, which are researched and used within the framework of the CRC 653 [11, 12]. These sensors permit the use of small notch geometries and consequently lead to less influence on the structural rigidity. The design of one of the notch geometries is illustrated in Fig. 3.2.1.2B. As accessibility is of great importance for the application of the sensors, a chamfer with an angle of 90–120 degrees is chosen. Additionally, the depth of the notch is restricted to 2–4 mm due to the material thickness of the slide. The notch has a parabolic curved ground to increase strain maxima. The curved ground transits to a linear slope from the respective tangents. To achieve high strain amplitudes in the notch ground, parametrical FE simulations were conducted to determine the optimal profile parameters. Within the simulations, the parable ordinal number $n$ and the parable width $h$ are varied to compute the maximal amplification factors with the given geometrical boundary conditions. As the result of these simulations, the amplification factor of the measurable strains compared to nonnotched surface measurement is shown in Fig. 3.2.1.2C as a function of $h$ and $n$. As can be seen, decreasing $h$ and $n$ leads to higher strain amplification.

### 3.2.1.4 Developed machine components

A sensory spindle slide is realized prototypically and integrated into a milling center DMG HSC55 linear [9, 10] (Fig. 3.2.1.3). For the strain detection, miniature strain gauges are integrated into the manufactured small notches in the spindle slide. Two different kinds of miniature strain gauges, which were developed within the CRC 653, are applied: the first kind includes laser structured strain gauges (L-SG) which are directly sputtered on the 3D surface and subsequently structured using a laser beam [11]. The second kind consists of micro strain gauges which are based on a flexible polymer substrate and can only be applied to flat surfaces ($\mu$-SG) [12]. These strain gauges are applied in 12 positions across the slide structure. These positions correspond to locations in the spindle slide which exhibit the highest sensitivity to mechanical strain as calculated from FE simulations. All used strain gauges are connected to electronic signal processing devices to compute and communicate the signals to the unit control. Because of the negligible dimensions of the notches compared to the slide, the change of the slide stiffness due to the notches lies in the range of 0.1% (Fig. 3.2.1.4A). Their influence can therefore be ignored.

Fig. 3.2.1.4B shows the sensing sensitivities of the strain gauges in the positions P1 to P4 according to static forces at the slide TCP in the directions $x$, $y$, and $z$. In general, the strain gauges integrated in the notch (L-SG, $\mu$-SG) clearly show a big increase in the sensitivity to load compared to conventional strain gauges (Ref.) which are located very closely to the positions but are not integrated in notches. In comparison to the $x$- and $y$-directions, the spindle slide is not sensitive to load in the $z$-direction. This is due to the higher stiffness of the slide in this direction.
3.2.1.5 Force calibration by machine components

The aim of the force calibration is to determine mathematical matrices which are able to convert the signals of the strain gauges into force signals. The calibration matrices are computed using a linear regression analysis using reference force signals and all strain signals of the spindle slide.

With respect to the spindle slide, the low sensitivity in the $z$-direction impedes the force measurement in this direction. This is why the calibration neglects this force. The forces in the $x$- and $y$-directions can be detected accurately due to the high sensitivity to load of the strain gauges. Because each integrated strain gauges is sensitive

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**Fig. 3.2.1.3** Integrated sensory components in the test machine tool.
in both directions, the force calibration depends on how the load force is applied at the TCP. Two situations can be distinguished: the first situation arises during the milling process. During this process, process forces are applied simultaneously in the $x$-, $y$-, and $z$-directions. Each strain gauge provides a signal as a response to the combined loads from both directions. In this case, the calibrations of the $x$- and $y$-forces should be computed in parallel using the process forces. The second situation occurs in offline applications where forces are used to statically excite the slide in only one direction, either the $x$- or $y$-direction, such as the stiffness measurement of the spindle slide or the tool. Each strain gauge delivers a signal as a response to a simple load direction. In this case, the slide calibration in $x$- and $y$-direction should be carried out separately using statically applied forces at the TCP.

In the offline force calibration, the reference force signals are measured by a conventional force sensor. Fig. 3.2.1.5A shows the reference forces and the forces of the spindle slide measured after static calibration. In the in-process calibration, the signals are measured during up and down milling, where only the cutting depth is changing.
Fig. 3.2.1.5 (A) Offline force calibration of the spindle slide and (B) calibration of the spindle slide forces using process signals.
The reference forces are provided by a dynamometer. The filtered reference forces and the filtered forces of the spindle slide after calibration are mapped in Fig. 3.2.1.5B. This figure shows that the forces of the spindle slide can be approximated well with standard linear regression for both calibration methods. The calculated deviations of the forces to the reference grow to maximal 10% in the range of 500 N, where the force resolution is about 10 N. The calculated forces of the spindle slide based on the offline calibration are also depicted in Fig. 3.2.1.5B. A comparison of these forces with the reference forces shows a deviation up to 40 N that can occur when an unsuitable force calibration method is used.

### 3.2.1.6 Conclusion and outlook

This chapter describes the development of “feeling” machine tools by the integration of strain gauges into selected machine components. The use of the notching effect shows a significant improvement of the component sensitivity and the measuring quality of forces without lowering the component stiffness. Chapters 3.2.2 and 3.2.3 describe the development of further “feeling” machine components and even “feeling” workpieces. Based on the provided force signals from the “feeling” machine tool, process monitoring and process control systems can be enabled. Chapter 3.2.5 presents an approach for the monitoring and control of the tool deflection in milling.

### References


